APPENDIX A

EXECUTIVE SUMMARY, PROJECT MOHAVE FINAL REPORT, SUBMITTED TO THE USEPA
MARCH 1999

EXECUTIVE SUMMARY

Purpose

The purpose of this report is to communicate the consensus data interpretation of the principal partners in Project Measurement of Haze and Visual Effects (MOHAVE) concerning the nature, extent, and frequency of Mohave Power Project (MPP) contributions to haze at the Grand Canyon National Park (GCNP).

Introduction

Project MOHAVE was an extensive monitoring, modeling, and data assessment project designed to estimate the contributions of the MPP to haze at GCNP. The field study component of the project was conducted in 1992 and contained two intensive monitoring periods (~30 days in the winter and ~50 days in the summer). Unique, non-depositing, non-reactive perfluorocarbon tracer (PFT) materials were continuously released from the MPP stack during the two intensive periods to enable the tracking of emissions specifically from MPP. Tracer, ambient particulate composition, and SO_2 concentrations were measured at about 30 locations in a four-state region. Figure A is a map of the area showing the locations of MPP, GCNP, and the monitoring sites. Two of these monitoring sites, Hopi Point (HOPO) near the main visitor center at the south rim of the canyon and Meadview (MEAD) near the far western end of the national park were used as key receptor sites representative of GCNP.

Project MOHAVE operated under the joint technical and program management of the Environmental Protection Agency (EPA) and Southern California Edison (SCE) in close partnership with the National Park Service (NPS). Numerous other organizations contributed to the operations and assessment work of the project. Since the end of the field study component of the project, data assessment and modeling efforts were undertaken by the many participants and have led to numerous papers and reports. By design these efforts have been the products of their respective authors and have not been endorsed as findings of Project MOHAVE.

The process of identifying and quantifying the impact of MPP's emissions on Grand Canyon visibility was accomplished using two types of assessment methodologies. The first method, known as receptor modeling, is an empirical assessment of the extensive data collected during the study to estimate the MPP's presence and quantify the resulting atmospheric response, such as an increase in particulate sulfur, MPP tracer, or light scattering. The advantage of this method is that it provides a ground truth and answers the question: do the measurements confirm the presence of the MPP plume? The disadvantages of this method are that measurements cannot be collected everywhere all the time. The second method relies on the application of mathematical models to describe the transport and chemistry of MPP's emissions. Such models also make use of the measurements and can provide predictions at all locations for all times. However, they can provide highly uncertain results due to their lack of complete knowledge of the complex atmospheric transport, dispersion and chemical processes involved in the formation of visibility-

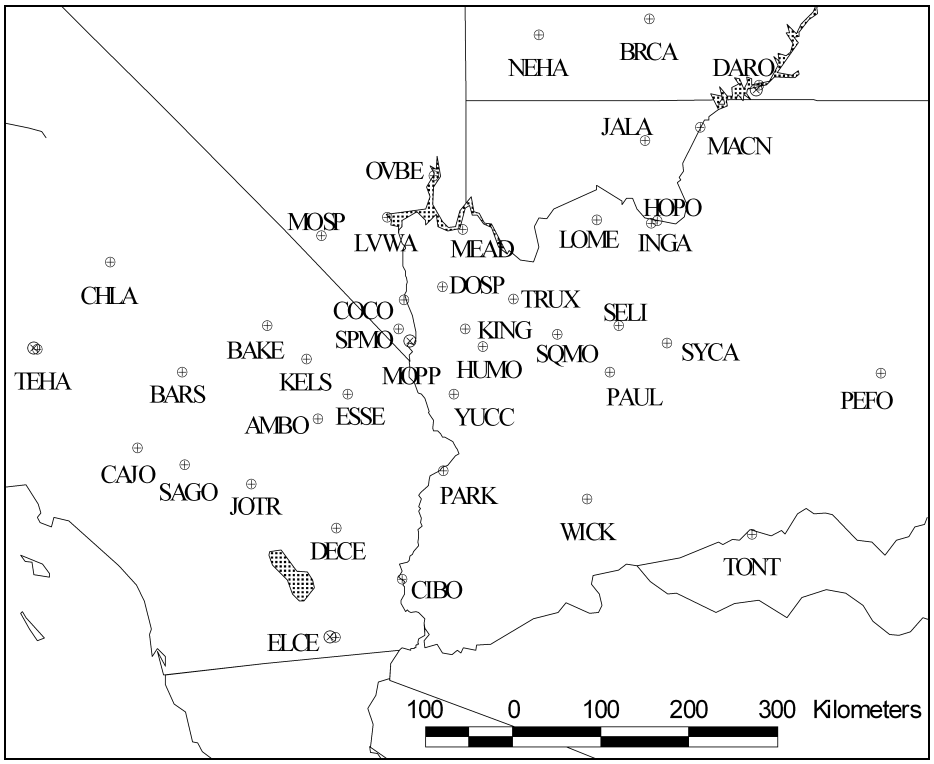

Figure A Project MOHAVE Site Map

Abbreviation	Location	Abbreviation	Location
AMBO	Amboy	LVWA	Las Vegas Wash
BAKE	Baker	MACN	Marble Canyon
BARS	Barstow	MEAD	Meadview
BRCA	Bryce Canyon	MOPP	Mohave Power Plant
CAJO	Cajon Pass	MOSP	Mountain Springs Summit
CHLA	China Lake/Ridgecrest	NEHA	New Harmony
CIBO	Cibola National Wildlife Refuge	OVBE	Overton Beach
COCO	Cottonwood Cove	PARK	Parker
DARO	Dangling Rope	PAUL	Paulden
DECE	Desert Center	PEFO	Petrified Forest National Park
DOSP	Dolan Springs	SAGO	San Gorgonio
ELCE	El Centro	SELI	Seligman
ESSE	Essex	SPMO	Spirit Mountain
HOPO	Hopi Point	SQMO	Squaw Mountain
HUMO	Hualapi Mountain	SYCA	Sycamore Canyon
INGA	Indian Gardens	TEHA	Tehachapi Summit
JALA	Jacob Lake	TONT	Tonto Natational Forest
JOTR	Joshua Tree	TRUX	Truxton
KELS	Kelso	WICK	Wickenburg
KING	Kingman	YUCC	Yucca
LOME	Long Mesa		

impairing aerosols. The summary below examines the results from both of the methodologies discussed above.

Many of the early efforts to estimate the contribution of MPP to haze at GCNP using various models of both types were done prior to the release of the tracer measurement data. This was done to provide a blind method to examine the accuracy of the assessment methods by comparing each method's estimate of tracer concentrations to measurement data at one or both key receptor sites. Correlations between measured tracer concentrations and predicted tracer

concentrations from the original assessments were poor indicating that the initial models could not be used to estimate the MPP impact.

Correlations between measured tracer concentration and both particulate sulfur and light extinction were virtually nil. While this suggests that MPP was not responsible for the majority of visibility impairment at Meadview, it does not indicate that MPP had no impact on visibility in the area. In order to better resolve MPP's contribution to haze at GCNP, a second round of assessments using new and more refined methods was initiated. Most of these methods used the PFT information in their analyses. This report focuses on the results of this second round of assessment methods. These methods are briefly described in Table A. Each of these methods estimates the MPP contribution to sulfate concentrations at one or both of the key receptor sites on a 12-hour or 24-hour basis corresponding to the sample periods for the particulate sample duration (0700 to 1900 MST and 1900 to 0700 MST).

Two of the assessment methods were used solely to estimate bounds between which the actual MPP contributions might lie. The Tracer Max method indicates the absolute maximum contribution of MPP that is physically possible, although such an impact is not considered reasonable. The CALPUFF model was used in two modes – CALPUFF Dry was used to calculate the amount of sulfate attributable to MPP if only the relatively slow gas phase conversion of SO_2 to sulfate took place, while CALPUFF Wet was used to approximate the MPP contribution if every day included 3 hours of in-cloud aqueous conversion at a rate of 20%/hr. By and large the results of the other modeling calculations tended to lie somewhere between those of CALPUFF Dry and CALPUFF Wet.

The results of the various methods have been assessed for reasonableness. For example, the amount of particulate sulfate from MPP should not exceed the total measured amount of sulfate, nor should it exceed an amount corresponding to 100% conversion and no deposition of the MPP SO_2 as determined from the measured tracer concentration (i.e., the Tracer Max calculation). Implicit in the results shown below is the assumption that tracer data are well measured (i.e. with good precision and accuracy) and truly represent the transport and dispersion of the MPP effluent. Collocated precision of the MPP tracer concentrations at Meadview was 7% of the average tracer concentration during the summer period. All of the second round methods with results summarized below have used the tracer concentration data either directly as input or indirectly to optimize or calibrate some aspect of the method.

Findings

Findings below are presented in bullet form and organized into two major categories: overview and specific findings. The overview includes a description of conditions required for MPP visibility impacts at GCNP and describes the process used to generate specific findings. The specific findings contain summaries of the MPP contributions to 12- and 24-hour particulate sulfate, MPP contribution to 12- and 24-hour extinction coefficient, and extrapolation to short-term MPP impacts during the two seasonal intensive monitoring periods and for other times of the year.

Table A Methods Used to Estimate Source Contributions

Method	Description	Inputs	Outputs
Receptor Data Analyses			
Tracer Max (Tracer Scaling)	Estimation of total sulfur impacts by scaling PFT measurements; provides upper bound for potential sulfate impacts	PFT, SO_2, and particulate S concentrations at receptors; emission ratio of SO_2/PFT;	Contribution of PFT source to ambient S; upper bound estimate of contribution to particulate S
Exploratory Data Analysis	Statistical analysis of SO_2, particulate sulfur, and PFT measurements	PFT, SO_2, and particulate S concentrations, and b_{sp} at receptors	Spatial correlations of particulate sulfur, temporal correlations of PFT, SO_2, and particulate S at specific sites
Tracer Regression	Regression of b_{ext} against PFT, industrial methylchloroform, and water vapor mixing ratio	PFT, methylchloroform, and mixing ratio measurements at receptors	Contributions to b_{ext} from emissions in source regions of the chosen tracers
TAGIT	Estimation of sulfate impact by identifying unimpacted sites from PFT measurements	PFT, SO_2, and particulate S concentrations at multiple receptors	SO_2 and particulate S concentrations attributable to sources/source regions where PFT was emitted
Modified CMB	Chemical mass balance receptor modeling, modified to account for conversion and deposition of SO_2 and sulfate	Source/source-regions and receptor concentrations of SO_2, sulfate, and markers -- elements, spherical aluminosilicate, b_{abs}; relative times of travel; ROME estimates of relative conversion rates for emissions from different sources/source-regions.	SO_x and sulfate attributable to sources/source- regions
TMBR	Tracer mass balance regressions of SO_2 against PFT and of particulate S against PFT	Concentrations at receptors of PFT, SO_2, and particulate sulfur	SO_2 and particulate S concentrations attributable to MPP
DMBR	Differential mass balance regression; hybrid of tracer-based dilution calculation with parameterized deposition and conversion	Concentrations at receptors of PFT and SO_2; times of travel from source to receptors; estimates of conversion rates; index of cloud cover	SO_2 and particulate S concentrations attributable to MPP
Source Emissions Simulations			
HAZEPUFF (Modified)	Lagrangian puff model; interpolated wind field; first order sulfate chemistry; modified dispersion classes	Wind profiler soundings, PFT and SO_2 emissions from MPP, relative humidity	Plume locations and concentrations of PFT, SO_2, sulfate, and light scattering attributable to MPP
CALPUFF/ CALMET	Multi-layer Gaussian puff model with parameterized first order chemical conversion; diagnostic meteorological model	Surface and upper air meteorological data, topography, PFT and SO_2 emissions from MPP, solar radiation, ambient O_3	Distribution of concentrations of PFT, SO_2 and sulfate attributable to MPP
ROME/ RAPTAD/ HOTMAC	Lagrangian plume model with explicit reaction chemistry; three-dimensional Lagrangian random puff dispersion; primitive equation meteorological model	Meteorological soundings, topography and land use, solar radiation; MPP emissions of PFT, SO_2, NO_x, and trace metals; background chemical concentrations; PFT concentrations at receptors	Concentrations of PFT, SO_2 and sulfate in MPP plume, at surface and aloft

Overview

- From a meteorological, visibility, and sulfate concentration perspective, the Project MOHAVE study year (1992) is representative of longer periods of record. Minor exceptions to that statement include that the winter of 1992 was somewhat more moist (clouds and precipitation) than the 15 year average; the summer of 1992 was one of the cleaner summers

on record at Hopi Point with less severe conditions for the poor visibility periods; Meadview summer 1992 sulfate concentrations were comparable to summer sulfate levels during the 5-year SCENES monitoring period (1984 - 1989).

- Based on climate records, MPP emissions are usually transported towards the western end of GCNP by wind flow from the south in the summer (April through September) and away from GCNP by flow from the north in the winter (November through February). These wind patterns also cause flow of emissions towards GCNP from source areas to the southwest in the summer such as Southern California, northern Mexico, and the San Joaquin Valley and from sources to the northeast in the winter such as the Navajo Generating Station.

- PFT released from MPP during the winter and summer intensive monitoring periods corroborated the earlier finding that the greatest frequency of transport from MPP to GCNP was during the summer.

- During the summer intensive monitoring period, sites around Lake Mead (Meadview, Overton Beach, and Las Vegas Wash) recorded tracer concentrations above background levels on over 90% of the days; at Hopi Point, tracer was above background concentrations on about half of the days.

- During the winter intensive monitoring period, Meadview recorded MPP tracer concentrations above background levels during about 6% of the days; at Hopi Point, MPP tracer concentration were never measured above background levels.

- Project MOHAVE analysts found negligible correlation between measured MPP tracer concentrations and visibility impairment at Meadview or Hopi Point. The absence of any obvious relationship cannot rule out MPP contributions to haze in GCNP, but strongly suggests that other sources were primarily responsible for the haze.

- Other analyses (summarized in the body of the report), done as part of Project MOHAVE, show that during the summer intensive period there was clear observational evidence linking emissions from distant urban areas such as Southern California to visual impairment at GCNP. These analyses corroborate earlier findings by other investigators who have used techniques designed to specifically identify the presence of the Southern California emission plume.

- From the tracer data and the known ratio of tracer to primary particle emission rates during normal operations of MPP, primary particles from MPP disperse during transport to GCNP to the extent that though they contribute to visibility impacts they alone would not cause noticeable impairment.

- From the tracer data and the known ratio of tracer to SO_2 emission rates for MPP, SO_2 emitted by MPP often reaches Meadview in sufficiently high concentrations to have the potential to cause impairment (See Tracer Max in Table A). Thus, the critical factor in determining the impact of MPP is knowledge of the particulate sulfate production in the atmosphere by conversion of SO_2.

Technical Note - Conversion of SO_2 to sulfate occurs by two different mechanisms: dry or gas-phase chemistry and wet or aqueous-phase chemistry. The rate of dry conversion is slow and greatest during the daylight hours. Wet chemistry is relatively fast but its occurrence is harder to predict since it requires interaction of the SO_2 emissions with liquid water (e.g., in hygroscopic aerosols or cloud droplets) and the presence of oxidants to convert the SO_2 in the liquid phase.

- Project MOHAVE employed a number of methodologies (Table A) to estimate the contribution of MPP to particulate sulfate. With two exceptions (TMBR and TAGIT), these methods had to explicitly determine or use assumed rates of SO_2 to sulfate conversion for each time period during transport from MPP to GCNP. Much of the difference between the various methods is due to the differences in the predicted magnitudes of conversion that derive from assumptions concerning the interactions between emissions and clouds and calculations of emission travel times.

- The various methods do not agree unanimously on which are the most MPP-influenced time periods. The TAGIT method in particular identifies several high impact days that have low estimated MPP impact based upon other methods. The opposite is also true. While logic dictates that not all of the methods can be correct when there are substantial disagreements, there is no consensus concerning which of the methods is more likely to be correct for any particular time period. For these reasons the results from any specific method on any specific date are not ascribed substantial credibility.

- When the results from each of the various methods are sorted by magnitude of MPP impact, the resulting frequency distributions are similar. In other words the various methods tend to agree better concerning the magnitude of a typical MPP contribution (i.e. median or 50^{th} percentile) and for a greater MPP contribution (defined for this report as the 90^{th} percentile) than they do concerning the magnitude for any specific date in 1992. Thus, in order to interpret the attribution results, this report focuses on the range of results for typical and greater MPP contributions as defined by the 50^{th} and 90^{th} percentiles of the frequency distributions of the various methods, while recognizing that such a focus hides the lack of day-to-day agreement between the methods.

- All of the assessment methods except for TAGIT are able to estimate 12-hour MPP particulate sulfate concentrations corresponding to the sample periods at Meadview and Hopi Point. TAGIT is restricted to results for 24-hour duration, corresponding to two sample periods. The relative magnitude of the estimated MPP sulfate is easily determined by dividing the estimated sulfate by the coincident measured total sulfate.

Technical Note - Light extinction coefficient, an optical parameter that increases as visual range decreases and is related to the particulate concentration, is used to quantify visibility in this assessment. The higher the fractional contribution of an emission source to light extinction coefficient the greater is its visibility impact. A CD-ROM with viewing software and computer simulated views is provided with this report to illustrate the appearance of the magnitudes of changes reported in the tables below.

- Estimated relative MPP contribution to the light extinction coefficient was determined by two methods. In both, the first step was to convert each estimated MPP sulfate concentration to a light extinction coefficient value. Based on theoretical analyses of Project MOHAVE measurements, a sulfate extinction efficiency was derived specifically for the sulfate aerosol in the study area. In one method the results of the first step were divided by the corresponding measured light extinction coefficient values, while in the other they were divided by the typically somewhat smaller calculated extinction coefficient values determined from the measured aerosol composition data.[1] In all cases the effects of relative humidity on aerosol size are included in the calculations.

- A number of approaches were used to estimate the ratio of the highest short-term (e.g. 3-hour duration) to 12- or 24-hour duration relative extinction coefficient impacts in order to estimate the short-term impacts. Some of the methods used a limited data set of high time resolution tracer data measured at Meadview, others used the hourly estimated concentrations from the air quality models (e.g. CALPUFF).

- To examine the issue of impacts during the non-intensive monitoring periods, one of the apportionment methods (CALPUFF Dry) that can be implemented without the use of tracer data was used to estimate the particulate sulfate and fraction of extinction coefficient for other times of the year. Ratios of these estimates to corresponding estimates for the months containing the summer intensive period are used to assess the relative importance of MPP during other times of the year.

- One of the most interesting periods during the summer of 1992 was the two days following the discontinuation of tracer release from MPP at 0700 on August 31. Although visibility levels were not unusual, the first two days in September had the highest sulfate measurements recorded throughout the area that summer and represent some of the highest measurements ever made in the area. Winds were light and variable with flow reversals that could have increased the opportunity for SO_2 to sulfate conversion. Because of the lack of tracer data, only a few methods could be used to estimate the contribution of MPP. These are considered to have greater uncertainty than for periods with tracer data and are not included in the specific findings presented below. Some of the results of these showed relatively high MPP contribution to sulfate. However, there are alternative explanations that would indicate other sources are responsible for much of the measured sulfate.

Specific Findings

- The range of estimates by the various methods of MPP sulfate at Meadview and Hopi Point for the summer and winter at the 50th and 90th percentile are shown in Table B for the 12-hour time periods.

[1] The calculated extinctions did not match the measurements at times, and so both calculations are shown here.

Table B Range of estimated 12-hour MPP sulfate (ng/m^3) for the 50th and 90th percentile conditions. Model attribution results excluding the bounding estimates of CALPUFF Wet and Dry are shown in bold. Values in parentheses represent the ranges of all attribution results.

	Winter		Summer	
	50th	90th	50th	90th
Meadview	(0.0 to 0.0)	**40** (5 to 50)	**23** to **71** (23 to 93)	**120** to **320** (120 to 540)
Hopi Point	(0.0 to 0.0)	(0.0 to 0.0)	**4** to **27**	**38** to **160**

- Dividing each estimate of MPP sulfate by the measured coincident sulfate results in values shown in Table C that express the range of estimated percent of 12-hour sulfate contributed by MPP at key sites.

Table C Range of estimated 12-hour MPP fraction of measured sulfate (%) for the 50th and 90th percentile conditions. Model attribution results excluding the bounding estimates of CALPUFF Wet and Dry are shown in bold. Values in parentheses represent the ranges of all attribution results.

	Winter		Summer	
	50th	90th	50th	90th
Meadview	(0.0 to 0.0)	**3.5** (0.7 to 4.8)	**1.7** to **3.3** (1.7 to 8.0)	**8.7** to **21** (8.7 to 42)
Hopi Point	(0.0 to 0.0)	(0.0 to 0.0)	**0.4** to **1.6**	**3.1** to **13**

- Converting the 12-hour MPP sulfate estimates to light extinction coefficient and dividing by the coincident measured light extinction coefficient produces the results shown in Table D.

Table D Range of estimated 12-hour MPP fraction (%) of measured light extinction coefficient for the 50th and 90th percentile conditions. Model attribution results excluding the bounding estimates of CALPUFF Wet and Dry are shown in bold. Values in parentheses represent the ranges of all attribution results.

	Winter		Summer	
	50th	90th	50th	90th
Meadview	(0.0 to 0.0)	**0.1** (0.06 to 0.4)	**0.2** to **0.6** (0.2 to 1.0)	**1.3** to **2.8** (1.3 to 5.0)
Hopi Point	(0.0 to 0.0)	(0.0 to 0.0)	**0.1** to **0.4**	**0.5** to **2.6**

- If instead of dividing by the measured extinction coefficient, the estimated MPP light extinction were divided by the somewhat smaller calculated extinction coefficient, the range of values shown in Table E would result.

Table E Range of estimated 12-hour MPP fraction (%) of calculated light extinction coefficient for the 50th and 90th percentile conditions. Model attribution results excluding the bounding estimates of CALPUFF Wet and Dry are shown in bold. Values in parentheses represent the ranges of all attribution results.

	Winter		Summer	
	50th	90th	50th	90th
Meadview	(0.0 to 0.0)	**0.2** (0.1 to 0.4)	**0.3** to **0.8** (0.3 to 1.2)	**1.9** to **4.0** (1.9 to 6.7)
Hopi Point	(0.0 to 0.0)	(0.0 to 0.0)	**0.1** to **0.3**	**0.6** to **2.3**

- One of the methods (TAGIT) could only estimate the MPP contribution on a 24-hour basis. By averaging the 12-hour contributions of the various methods to 24-hour, results of all methods can be used together to estimate the 24-hour MPP contribution to extinction

coefficient. Table F contains the 24-hour average range of estimated MPP extinction coefficient percent of the coincident measured extinction coefficient.

Table F Range of estimated 24-hour MPP fraction (%) of measured light extinction coefficient for the 50th and 90th percentile conditions. Model attribution results excluding the bounding estimates of CALPUFF Wet and Dry are shown in bold. Values in parentheses represent the ranges of all attribution results.

	Winter		Summer	
	50th	90th	50th	90th
Meadview	(0.0 to 0.0)	**0.0** to **0.4**	**0.3** to **0.6** (0.3 to 1.5)	**0.9** to **3.5** (0.9 to 4.8)
Hopi Point	(0.0 to 0.0)	(0.0 to 0.0)	**0.0** to **0.4**	**1.1** to **5.3**[2]

- To examine the relative impacts of MPP on particulate sulfate during non-intensive monitoring periods, MPP estimated sulfate by one of the methods (CALPUFF Dry) which requires only the upper air measurements made at MPP (available from January to September 1992) were compared with corresponding estimates from the same method during the summer intensive period. Table G shows the ratio of the estimates for pairs of month compared to the July and August period that includes the summer intensive.

Table G Ratio of CALPUFF Dry estimated MPP 12-hour sulfate values for 50th and 90th percentile conditions for months not during the intensive monitoring period to corresponding values estimated for July and August.

	January & February		March & April		May & June	
	50th	90th	50th	90th	50th	90th
Meadview	0.0	0.2	0.5	0.8	0.4	0.6

- A similar approach is used to examine the relative impacts of MPP on extinction coefficient during non-intensive monitoring periods. Ratios of the CALPUFF dry estimates of the MPP fractional extinction coefficient for pairs of months to the July and August period that includes the summer intensive are shown in Table H.

Table H Ratio of CALPUFF Dry estimated 12-hour MPP fraction of the light extinction coefficient values for 50th and 90th percentile conditions for months not during the intensive monitoring period to corresponding values estimated for July and August.

	January & February		March & April		May & June	
	50th	90th	50th	90th	50th	90th
Meadview	0.0	0.5	0.7	0.9	0.4	0.7

- The previous two tables show that the CALPUFF estimated MPP contribution of sulfate and fraction of measured light extinction coefficient for March and April 1992 are nearly comparable to the CALPUFF estimated MPP contributions for the summer intensive period (i.e., ratios near 1). Note that because there is no tracer or 12-hour sulfate data during the intervening time periods with which to compare model predictions, the results shown in the last two tables should be treated with caution.

[2] The author of the method (TAGIT) that produced this result believes that it has substantial uncertainty as applied to MPP impacts at Hopi Point. The value associated with the next highest method for the 90th percentile is 2.5%, which seems to be a more reasonable upper limit.

- Though results of the various methods to estimate the daily short-term impacts from the 12- or 24-hour average impacts included substantial uncertainties, a ratio of about 2 seems to be a reasonable consensus value at Meadview for periods of greatest MPP impacts. In other words the maximum short-term impacts on any day at the 90th percentile are thought to be about a factor of two higher than the longer-term impacts listed in the tables above for Meadview.

- Some idea of the potential for extreme impacts, beyond the 90^{th} percentiles shown in Table D and Table E above, can be obtained from the greatest individual-day MPP attributions generated over the entire tracer period. The study-maximum estimated MPP contribution to Meadview light extinction during an individual 12-hour monitoring period was from about 2.5% to 8%, depending on the estimation method, with bounding values between 2.5% and 16%. This wide range of estimates underscores the fact that the disagreement among estimates was greatest when estimating infrequent conditions such as those that occur less than 10% of the time.

- The range of 90^{th} percentile values is less than, and therefore consistent with, results of the Tracer Max method that yields an absolute upper bound obtained from the measured tracer concentrations. This method makes the assumption that all of the MPP sulfur emitted is converted to sulfate without depositional loss of either sulfur dioxide or sulfate during transport to Meadview. The approach eliminates any possibility of underestimation (see Tracer Max in Table A). The greatest possible 12-hour impact by this method is about 23%, which is necessarily an overestimate of the greatest actual MPP contribution to Meadview light extinction during the Project MOHAVE tracer period.

- Several different models with their related assumptions were used in this study. There is general agreement among them about the ranges of impacts that may occur 90% of the time. There is less agreement however, about less frequent high-impact events (which occur less than 10% of the time). In any case, empirical data (actual field measurements) show poor correlation between the presence of MPP tracer and visibility impairment in the GCNP. Project MOHAVE analysts were unable to find any data to directly corroborate the extreme values calculated by some of the models, as noted in the results tabulated above.